Flight Crew Fatigue VI: A Synthesis

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GANDER PH, ROSEKIND MR, GREGORY KB. *Flight crew fatigue VI: a synthesis.* **Aviat Space Environ Med 69(9,Suppl.):B49–60.**
Sleep, circadian rhythms, subjective fatigue, mood, nutrition, and physical symptoms were monitored in flight crews before, during, and after scheduled commercial operations. Duty-related changes in these measures were examined in four different types of air transport: short-haul fixed-wing; short-haul helicopter; domestic overnight cargo; and long-haul. The extent of these changes, and the duty-related and physiological factors contributing to them, are compared among the different operations. During all operations, the level of sleep loss was such that the majority of crewmembers would be expected to have become increasingly sleepy across trip days, with some experiencing performance decrements. In addition, during overnight cargo and long-haul operations, crewmembers were sometimes flying aircraft during the circadian low point in alertness and performance. Specific recommendations for reducing flight crew fatigue are offered for each operating environment.

THE FOUR NASA FIELD studies described in the previous papers (15,19–21) provide an unprecedented amount of information on the duty-related and psychophysiological factors contributing to flight crew fatigue in different types of flight operations. Particular emphasis was placed on the two major physiological causes of fatigue symptoms in aviation, namely the disruption of sleep and circadian rhythms. Subjective fatigue and mood, changes in diet, and reports of physical symptoms were also recorded. All of the operations produced measurable changes in at least some of these variables. However, the extent of the changes, and the duty-related factors responsible for them, were different in each environment. This paper reviews the major findings, highlighting the similarities and differences among the operations, and examining specific ways in which fatigue in these operations could be reduced.

Duty Characteristics

In all of these studies, flight crewmembers were monitored before, during, and after regularly scheduled commercial trip patterns. **Table I** compares (by one-way analysis of variance) the characteristics of the trips studied. Information for Table I came from crewmembers' daily logbooks, and from the notes kept by the cockpit observers who accompanied them throughout each trip (17). The table includes only those trips for which sufficient sleep data were available to permit within-subjects comparisons of pretrip, trip, and posttrip values. Post hoc comparisons were made using Tukey tests with Bonferroni correction.

The daytime short-haul operations (fixed-wing and helicopter) permitted crewmembers to sleep at night and crossed a maximum of one time zone per 24 h. This caused minimal disruption to the circadian clock, which programs sleep at night and activity during the day, with a 24 h sleep/wake cycle. However both operations included multiple flight segments on each duty day and other demands which could potentially affect flight crew fatigue. The fixed-wing trips took place in the eastern and central U.S., with considerable flying in high traffic-density airspace. They included more flight segments per duty day, and the shortest layovers, of any of the operations studied ($p < 0.01$ for all comparisons), and longer duty days than all other operations except long-haul ($p < 0.01$ for all comparisons).

The helicopter trips serviced the North Sea oil fields from Aberdeen, Scotland. Operating conditions were often difficult with poor weather, variable quality landing sites with few alternates, limited automation of aircraft, and operating near the limits of range and performance capabilities of the aircraft. In addition, the cockpits were often physically stressful with such factors as poor ventilation, high levels of vibration, and uncomfortable temperatures due to solar heating and the requirement to wear cold-water immersion suits. Helicopter crews flew shorter duty days with fewer segments, and had longer layovers than their short-haul fixed-wing counterparts ($p < 0.01$ for all comparisons).

The domestic overnight cargo trips, which took place in the eastern and central U.S., involved multiple flights per night and crossed no more than one time zone per 24 h. They included fewer flight hours per 24 h than any of the other operations ($p < 0.01$ for every comparison), and fewer duty hours per 24 h than the other fixed-wing operations ($p < 0.01$ for all comparisons). The layovers were longer than those on the short-haul fixed-wing trips, but shorter than those on the long-haul trips ($p < 0.01$ for all comparisons). However, night duty required trying to override the normal diurnal orientation of the

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TABLE I. OPERATION CHARACTERISTICS.

	Short-Haul Fixed-Wing	Short-Haul Helicopter	Overnight Cargo	Long-Haul	F
Mean # segments/24 h	5.1	3.0	2.8	1.2	416.0****
Mean flight hours/24 h	4.5	3.6	2.6	6.9	207.5****
Mean duty hours/24 h	10.7	7.3	7.1	10.2	93.4****
Mean layover hours/24 h	12.5	16.8	14.9	24.3	281.3****
Maximum time zones crossed/24 h	1	0	1	8	
Day or night flying?	day	day	night	both	
Trip duration	3–4 d	4–5 d	8 d	4–9 d	
Crew complement	2-person	2-person	3-person	3-person	
# crewmembers studied	44	22	34	25	

*** $p < 0.0001$.

circadian clock, and being out of step with the day/night cycle and the diurnal orientation of the rest of society (1,8,33,53).

The four long-haul patterns studied were return trips from the west coast of the U.S. to Singapore, New Zealand, and England, and from the east coast of the U.S. via Germany to India. Daytime and nighttime flights usually alternated. Duty days were longer than those in either helicopter or overnight cargo operations ($p < 0.01$ for both comparisons), and included 1–2 flights crossing multiple time zones. Long-haul crews had more flight time per duty day than any other group, and had the longest layovers ($p < 0.01$ for all comparisons). On these trips, neither the day/night cycle nor the duty/rest schedule provided a 24-h pattern to which the circadian clock could synchronize. In addition, the long duration of the flights might be expected to make these crews especially prone to the effects of time-on-task fatigue, including reduced vigilance and habituation (11).

Crewmember Characteristics

Individual attributes of the crewmembers monitored in each operations are compared (by one-way analyses of variance) in **Table II**. Information from Table II came from the Background Questionnaires completed by all participants. Post hoc comparisons were made using Tukey tests with Bonferroni correction.

The long-haul crewmembers were the oldest group ($p < 0.01$ for all comparisons). The short-haul fixed-wing crewmembers were also older than the overnight cargo and helicopter crewmembers ($p < 0.01$ for all comparisons). The same pattern was reflected in years of experience. Years of experience was taken as the largest value from among the following categories: years with present airline; years of military experience; years of airline experience; years of general aviation experience; other. For crewmembers who proceeded from military to commercial aviation, this statistic would represent an underestimate.

The long-haul crewmembers were heavier than the helicopter crewmembers ($p < 0.01$), and more morning-type than either the helicopter crews or the overnight cargo crews ($p < 0.01$ in both cases). This is consistent with the observation that people tend to become more morning-type as they get older. There is some evidence that older and more morning-type individuals may have more difficulty adapting to shift work and time-zone changes (23). On this basis, it could be argued that physiologically challenging long-haul operations should be by flown by younger crewmembers, rather than the current situation. However, it is not known to what extent experience can counteract the effects of age-related changes in sleep and the circadian clock to influence cockpit alertness and performance.

The helicopter crewmembers scored lower than the

TABLE II. CREWMEMBER CHARACTERISTICS.

	Short-Haul Fixed-Wing	Short-Haul Helicopter	Overnight Cargo	Long-Haul	F
Mean age (y)	43.0	34.3	37.6	52.7	56.77***
Mean experience (yr)	17.1	8.6	12.8	22.8	25.80***
Mean height (in)	70.6	70.7	70.2	71.0	0.59
Mean weight (lb)	174.8	164.8	178.4	181.6	3.63*
Personal Attributes Questionnaire					
Instrumentality	23.3	21.4	24.5	22.8	2.72*
Expressivity	22.3	19.6	22.9	22.1	3.43*
I + E	2.8	2.4	3.2	2.7	2.41
Work and Family Orientation					
Mastery	20.0	21.3	21.3	20.7	0.99
Competitiveness	12.6	12.3	13.2	13.6	0.82
Work	17.7	17.7	18.2	17.5	0.88
Eysenck Personality Inventory					
Neuroticism	6.6	8.2	5.1	6.6	2.19
Extraversion	10.9	9.5	11.0	9.4	1.42
Morningness/Eveningness	57.6	54.4	54.4	61.6	4.75**

* $0.05 > p > 0.01$; ** $0.01 > p > 0.001$; *** $p < 0.001$.

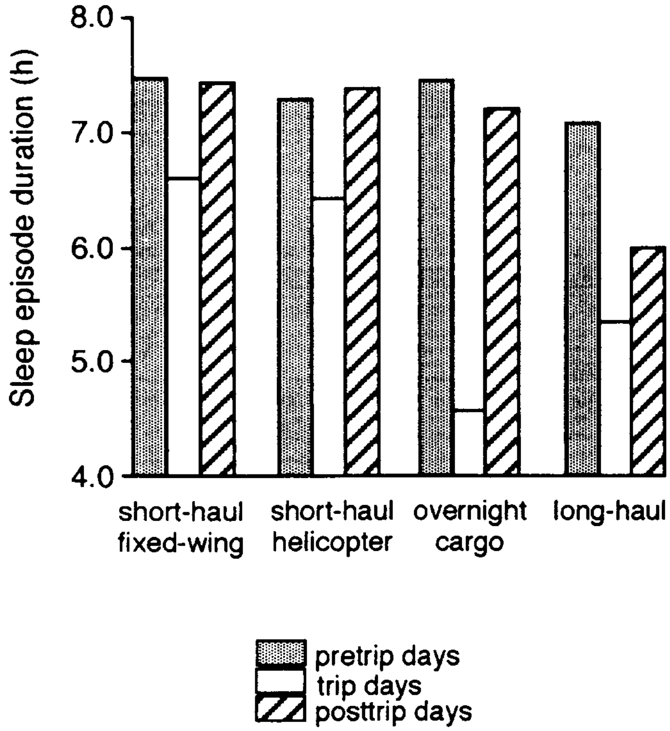

Fig. 1. Durations of individual sleep episodes on pretrip, trip, and posttrip days.

overnight cargo crewmembers on both the instrumentality and expressivity scales (27) of the Personal Attributes Questionnaire ($p < 0.01$ for both comparisons). It cannot be excluded that these differences were due to cultural factors, since the helicopter crews were British while the overnight cargo crews were U.S. citizens (the groups were comparable in age). Individuals scoring high on both scales have been reported to have better check airman ratings of flight crew performance (26) and to be more effective in group problem solving situations (41).

Duty-Related Changes in Sleep

Sleep quantity and quality were self-assessed in these studies. When they awoke from a sleep episode, crewmembers noted in their daily logbook the times of going to bed, falling asleep, waking up, and getting up. They also estimated how long they had slept (excluding time spent in bed awake) and how many times they had awakened during the sleep period. When they awoke from a nap, they noted the times of falling asleep and waking up. Long-haul flight crews have been shown to have a 95% probability of correctly estimating their objective sleep durations to within 0.5 h (10), but to be less reliable at estimating how long it takes to fall asleep, and how physiologically sleepy they are (24). It is not known how the reliability of other flight crews compares to that of the subjects in laboratory studies that have compared self-assessed and polygraphically recorded sleep parameters. Although subjective reports are less reliable than polygraphically confirmed sleep data, the measures used were internally consistent (16,20), and showed changes consistent with the different operational demands in each environment (15,19–21).

Duration of individual sleep episodes: In all operations, individual sleep episodes were consistently shorter on trip days than either pretrip or posttrip (**Fig. 1**). The changes in duration of sleep episodes across pretrip, trip, and posttrip days were compared among the operations by two-way ANOVA (**Table III**). The finding of shorter sleep episodes on trips was confirmed in the grouped data ($p(F) < 0.001$). Post hoc comparisons were made using Tukey tests with Bonferroni correction.

Sleep episode durations were not significantly different among the groups on pretrip or posttrip days. The significant interaction in Table III was due to the fact that, on trips, the overnight cargo and long-haul crewmembers had shorter sleep episodes than the short-haul fixed-wing crewmembers ($p < 0.01$ for overnight cargo, $p < 0.05$ for long-haul).

Quality of individual sleep episodes: On awakening, crewmembers rated their sleep quality (from 1 to 5) on the questions: Difficulty falling asleep?; How deep was your sleep?; Difficulty rising?; How rested do you feel?. These were converted so that higher scores indicated better sleep, and then added together to give an overall sleep quality rating. The changes in overall sleep quality across pretrip, trip, and posttrip days were compared among the operations by two-way ANOVA (Table III). Post hoc analyses indicated that trip sleep ratings were lower than posttrip ratings ($p < 0.01$), and tended to be lower than pretrip ratings ($p < 0.05$).

For each operation, pretip, trip, and posttrip sleep quality ratings (including the four individual ratings and the combined rating) were also compared by one-way analysis of variance, as reported in the preceding papers. These analyses indicate that, among the crewmembers who were consistently able to sleep at night during trips, the short-haul fixed-wing crews reported poorer sleep (20), whereas the helicopter crews did not (15). Possible reasons for this difference include:

- the fixed-wing crews were 9 yr older on average;
- they slept in layover hotels on trips, whereas the helicopter crews returned home each night;
- they markedly increased their alcohol consumption on trips by comparison with pretrip. Alcohol can facilitate falling asleep, but it also compromises sleep quality (4).

Overnight cargo crewmembers reported that their daytime sleep was lighter, less restful, and poorer overall than nighttime sleep (19). This contrasts with physiological recordings of daytime sleep among night workers in other industries (1) which indicate that daytime sleep is

TABLE III. DUTY-RELATED CHANGES IN SLEEP.

	F Pre/Trip/Post	F Flight Operation	F Interaction
Sleep episode duration (h)	67.10***	4.82**	7.51***
Total sleep per 24 h	49.81***	0.35	1.25
Overall sleep quality	5.84**	2.11	1.77

** $0.01 > p > 0.001$; *** $0.001 > p > 0.0001$.

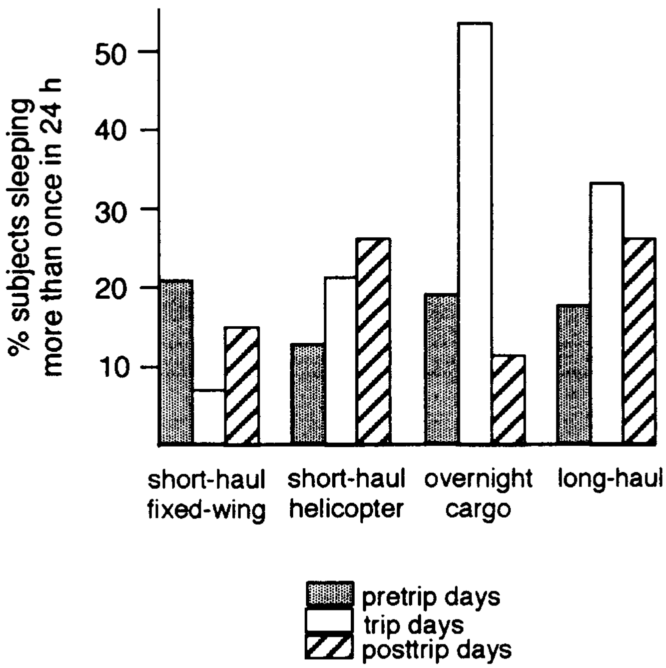

Fig. 2. Percentage of subjects sleeping more than once in 24 h (including naps) on pretrip, trip, and posttrip days.

usually shorter but deeper (deep slow-wave sleep being conserved at the expense of stage 2 NREM and REM sleep). The long-haul crewmembers did not report any significant changes in sleep quality on trips by comparison with pretrip (21).

Total sleep per 24 h: To compensate for markedly shorter sleep episodes on trip days, overnight cargo and long-haul crews tended to sleep more than once during each layover **(Fig. 2)**. It is somewhat misleading to consider the number of sleep episodes per 24 h during long-haul operations, because long periods of wakefulness associated with duty (average 20.6 h) alternated with layovers (averaging 24.8 h) during which crewmembers usually slept twice. In fact, long-haul crewmembers slept more than once in 68% of layovers, compared with 53% for overnight cargo crews. Long-haul layovers were significantly longer than overnight cargo layovers (Table I).

The changes in total sleep per 24 h across pretrip, trip, and posttrip days were compared among the operations by two-way ANOVA (Table III). Post hoc comparisons were made using Tukey tests with Bonferroni correction. Across all operations crewmembers averaged less total sleep on trip days (6.6 h) than on pretrip days (7.6 h) or posttrip days (7.7 h; $p < 0.01$ for both comparisons). This analysis did not find significant differences among the operations in the total amount of sleep per 24 h either pretrip, during trips, or posttrip. However, it does not take into account the greater prevalence of split sleep patterns during overnight cargo and long-haul trips. There was also considerable individual variability in sleep loss* in all operations. This is reflected in **Fig. 3**, which shows the percentages of subjects who averaged daily sleep gain or daily sleep loss across the different operations.

Cumulative sleep debt: Averaging a daily sleep loss across a trip pattern leads to the accumulation of a sleep debt. By the end of a 4-d short-haul trip, a crewmember averaging 2 h of sleep loss per 24 h would have lost a total of 8 h of sleep. By the end of the 8-d overnight cargo trips, even with the recuperation on the night off, 29% of crewmembers had accumulated a sleep deficit of more than 16 h, roughly equivalent to 2 complete nights of sleep. By the end of the 8-d "London" long-haul trip, 33% of crewmembers had accumulated a sleep deficit of more than 16 h.

Significance of duty-related changes in sleep: No objective measures of alertness or performance were collected during these studies, and no fatigue-related safety incidents were observed. Nevertheless, data from laboratory studies suggest that the observed levels of sleep loss might be expected to have reduced crewmembers' functional capacity in some cases.

Reducing sleep by 2 h on 1 night in the laboratory increases subsequent sleepiness and can impair performance on a variety of tasks. It also causes consistent changes in the structure of sleep (shorter sleep latencies and deeper, more consolidated sleep) that are considered to indicate insufficient sleep (7). The effects of reducing

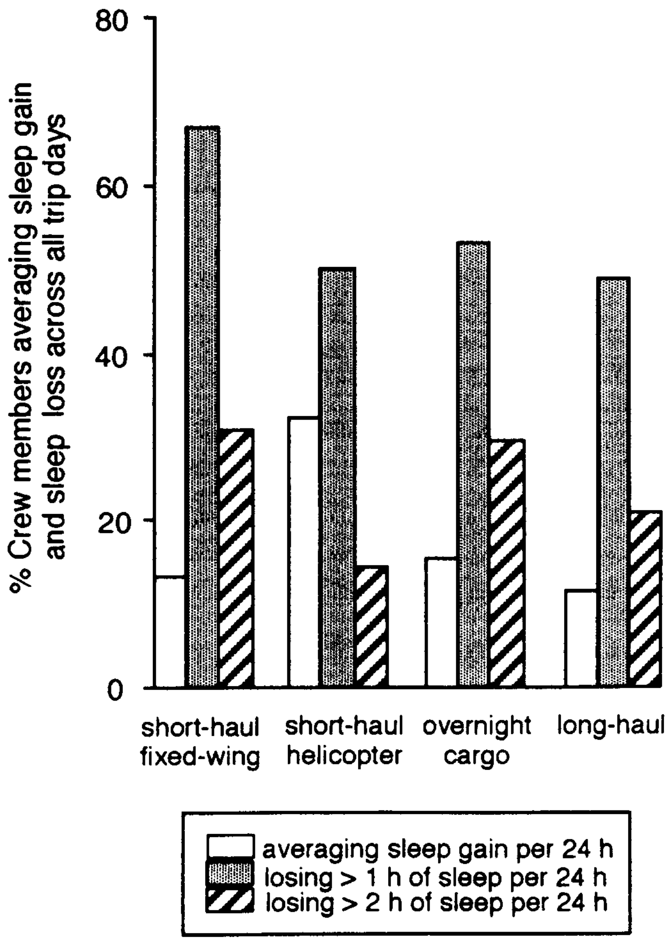

Fig. 3. Average sleep loss across the entire trip during different operations.

*To calculate individual sleep loss for each crewmember, his total sleep per 24 h on trips was subtracted from his average total sleep per 24 h at home pretrip.

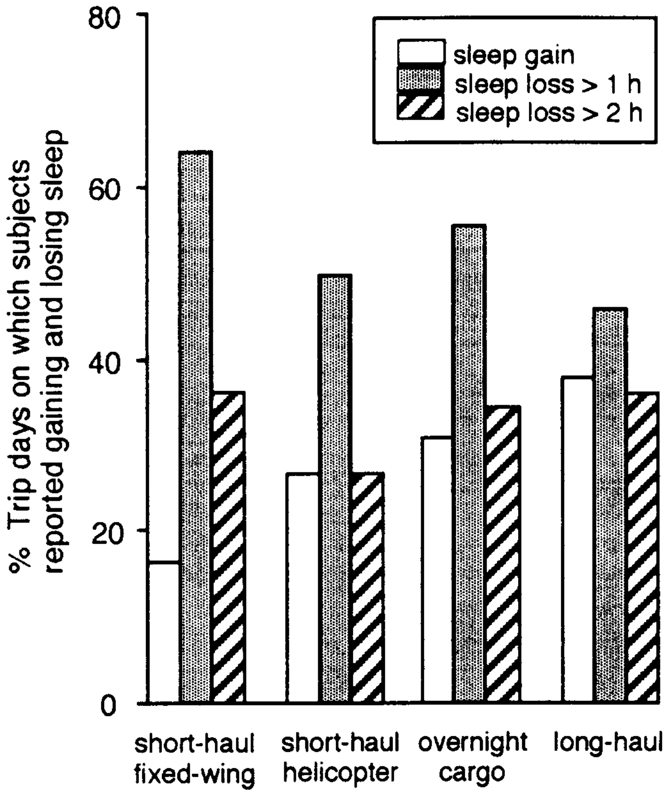

Fig. 4. Acute sleep loss (or gain) during different operations.

sleep by as little as 1 h per night accumulate over time to increase daytime sleepiness progressively (6).

Taking these values as benchmarks, the percentage of trip days on which crewmembers reported losing 1 or 2 h of sleep were calculated for each operation **(Fig. 4)**. The estimates of sleep loss during fixed-wing short-haul operations are exaggerated because a number of crewmembers took strategic naps on the final pretrip day (20). This inflated their total pretrip sleep duration, against which their subsequent sleep loss was calculated. Recall also that the long-haul crewmembers had a non-24 h duty/rest pattern. Fig. 4 suggests that, across all the operations, on any trip day about half the crewmembers were suffering from 1 h of acute sleep loss, and about one-third were suffering from 2 h of acute sleep loss. However, these figures may well underestimate the increased potential for error due to sleep loss on trips. They consider only the total sleep per 24 h and do not address the effects of split sleep during overnight cargo and long-haul layovers, or the effects of reduced sleep quality, which can also impair subsequent waketime function (47). Further, they do not address the cumulative effects when sleep is restricted across a series of consecutive days, as in these operations.

Individual attributes and duty-related sleep loss: A variety of analyses were carried out in an attempt to identify individual attributes that might explain the large variability in sleep loss observed among crewmembers during trips. Among overnight cargo crews (19), the average daily percentage sleep loss on trips was not correlated with any of the attributes reported by others to predict adaptation to shift work, namely: the amplitude of the pretrip baseline temperature rhythm (43,51); the neuroticism and extroversion scales of the Eysenck Personality Inventory (9,12,22); and morning/eveningness (2,13,28–30,33,35,50). A meta-analysis was carried out on a combined data pool from 91 U.S. commercial and military flight crewmembers aged 20–60 yr (23). Multiple regression analyses were used to assess the contributions of the following individual attributes to the variance in the average daily percentage sleep loss on trips: age; neuroticism; extroversion; morning/eveningness scores; the amplitude of the baseline temperature rhythm; and the local time of its daily minimum. The phase and amplitude of the baseline temperature rhythm were the only significant predictors of sleep loss while on duty, accounting together for about 8% of the variance. It should be noted, however, that the age distributions of crewmembers in each type of operation were different, so that different operational demands may have camouflaged the contribution of other (unidentified) age-dependent effects on sleep loss. In a combined data set of military and commercial long-haul crews ($n = 67$, age range 20–60 yr), there was a significant increase in the average daily percentage sleep loss on trips with age (one-way ANOVA with age in 10 yr bins, $F = 3.36$, $p < 0.05$).

Duty-related Changes in the Circadian Temperature Rhythm

In these studies, the time-course of the circadian clock was estimated from the rhythm of rectal temperature measured at 2-min intervals. To reduce the masking of the circadian variation in temperature by shorter-term fluctuations caused by changes in physical activity, a constant (0.28°C) was added to each crewmember's temperature data whenever he reported being asleep. The effects of this mathematical unmasking technique on estimation of circadian parameters have been described in detail elsewhere (18). Both masked and unmasked temperature data were subjected to multiple complex demodulation to estimate the times of the cycle-by-cycle minima (42).

In both the short-haul operations studied, layovers coincided with local night and no more than one time zone was crossed in 24 h. This permitted the circadian clock to remain synchronized to local time. However, during both operations, crewmembers averaged about 1 h of sleep loss per day because they were unable to go to sleep early enough to compensate for having to wake up 1.5 h earlier than usual to go on duty. Circadian factors oppose falling asleep earlier than usual. The evening wake maintenance zone is centered several hours before the usual bedtime (52). This is a part of the circadian cycle where it can be difficult to fall asleep, even with a moderate sleep debt. In addition, the innate period of the human circadian clock is usually around 25 h (52,55). Consequently, it is easier to fall asleep later than usual, rather than earlier. This effect is reinforced by the increase in sleep drive caused by staying awake longer (3,7). Thus, even in the short-haul operating environments, the circadian clock was restricting the amount of layover time that was available for sleep.

Overnight cargo operations required crews to fly for up to 5 consecutive nights, crossing no more than 1 time

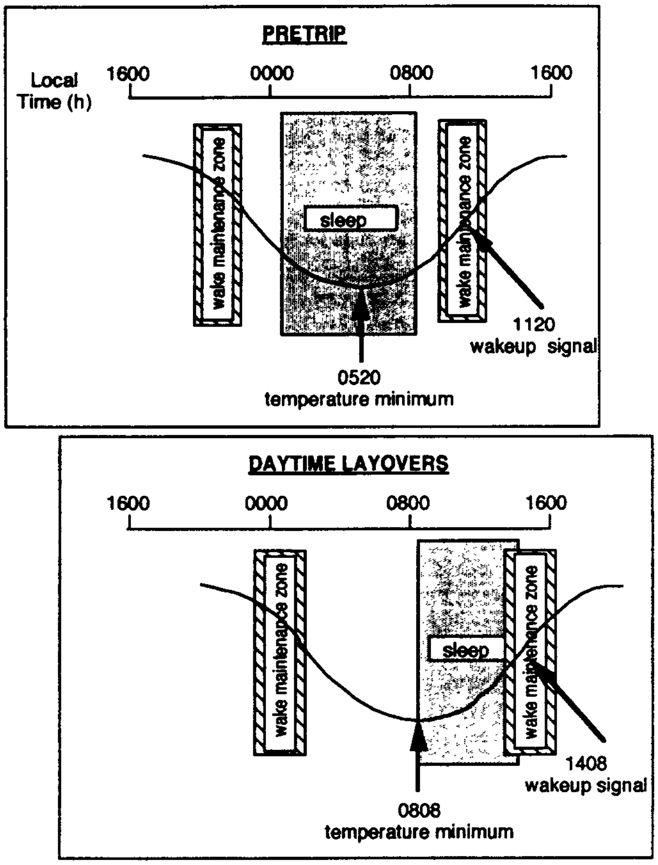

Fig. 5. Schematic showing the timing of sleep with respect to the circadian temperature rhythm, for overnight cargo crewmembers on pretrip and trip days. The average sleep times are indicated as shaded rectangles. The circadian temperature rhythm is approximated by the sinusoid, with the average time of the unmasked temperature minimum indicated. The timing of the wake maintenance zones and the wakeup signal have been extrapolated, based on reference 52.

zone per 24 h. In keeping with findings for night workers in other industries, the temperature rhythm showed minimal adaptation to night flying, delaying by an average of about 3 h (1,33,53). One consequence of this incomplete adaptation was that crewmembers were often on duty around the time of the temperature minimum (19). At this time, their physiological sleepiness and subjective fatigue would be expected to be greatest, and their performance to be poorest (1,9,31,32,34,47). Another consequence of incomplete circadian adaptation to night duty was that crewmembers were forced to sleep later in the circadian cycle after night duty than they did when they were able to sleep at night. This is illustrated in **Fig. 5.** It is noteworthy that the average time of waking up from morning sleep episodes was 1413 hours local time, and the average expected time of the circadian wakeup signal (6 h after the temperature minimum) was 1408 hours. Crewmembers did not record what caused them to wake up, but they did indicate that they did not feel well-rested after morning sleep episodes, which were markedly shorter than their normal nighttime sleep. These findings suggest that the circadian clock may well have been restricting the amount of layover time available for sleep.

In long-haul operations, the combination of non-24 h duty-rest cycles, alternating daytime and nighttime flying, and flights crossing up to 8 time zones, together created erratic environmental time cues that the circadian clock could not follow.[†] Some 80% of crewmembers continued to exhibit circadian variation in temperature, with an average cycle length of 25.7 h (SD 1.3 h). The remaining 20% of crewmembers had no detectable circadian rhythmicity in temperature. Because the average duty/rest cycle was about 35 h (Table I), the circadian temperature minimum, and hence the low point in alertness and performance, sometimes occurred in flight (21).

Sleep timing during long-haul layovers was linked to the circadian temperature cycle (21). This is illustrated in **Fig. 6.** During layovers, the average time of sleep onset was 2 min after the temperature minimum and the average time of wakeup was 6.4 h after the temperature minimum; or around the expected time of the circadian wakeup signal. This closely resembles the patterning of sleep observed with people living in time-free environments who spontaneously adopt a sleep/wake cycle dif-

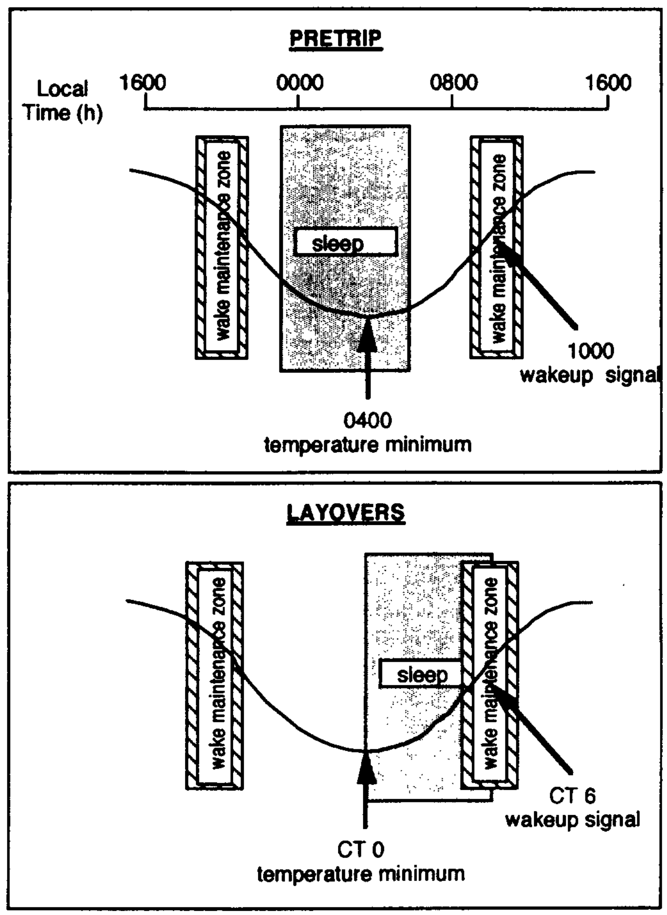

Fig. 6. Schematic showing the timing of sleep with respect to the circadian temperature rhythm, for long-haul crewmembers on pretrip and trip days (see Fig. 5 for explanation). During these operations, consecutive layovers were usually in different time zones, and the circadian clocks of most crewmembers drifted away from a 24 h cycle. Thus, neither local time nor GMT are suitable time reference scales for these data. They are therefore referenced to the circadian temperature cycle.

[†]Linear-nonlinear least squares iterative multiple regression was used to search for significant periodicities in the temperature data (48).

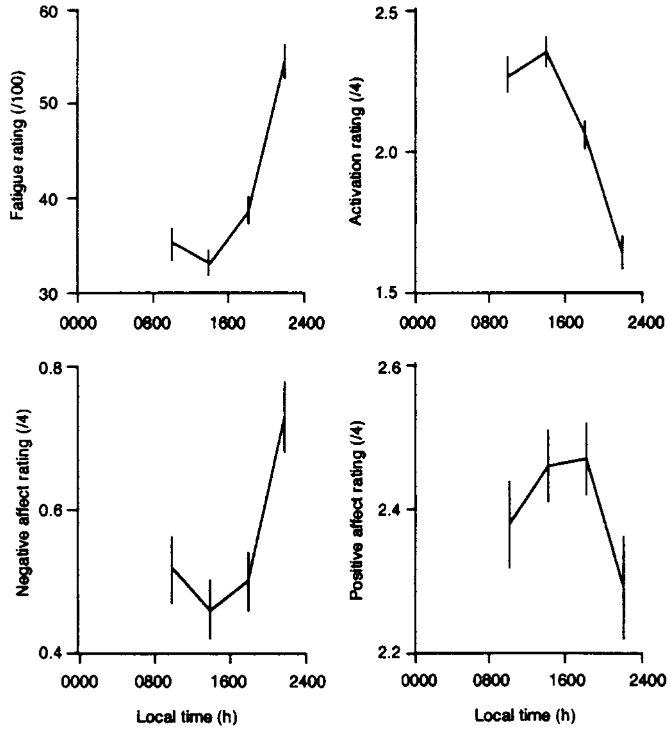

Fig. 7. Time-of-day variation in pretrip fatigue and mood ratings. These are combined data for 69 crewmembers from all four operations (one-way ANOVA with fatigue ratings in 4-h bins, $F = 52.0$, $p < 0.001$). Vertical bars indicate standard errors.

ferent from the period of the circadian temperature rhythm (52). On layovers, long-haul crewmembers were sleeping in a similar part of the circadian cycle to overnight cargo crewmembers. However, the long-haul crews selected to sleep at these times, within layovers averaging about 25 h, and they tended to sleep during local night. In contrast, the overnight cargo crews had layovers that averaged about 16 h and that were confined primarily to the daylight hours. Interestingly, the long-haul crews did not experience the reduction in sleep quality on trips that the overnight cargo crews reported.

Duty-Related Changes in Subjective Fatigue

Crewmembers indicated their subjective feelings of fatigue every 2 h while they were awake, by placing a mark on a 10-cm line from very alert to very drowsy. This measure of subjectve fatigue was not significantly correlated with how rapidly long-haul crewmembers fell asleep in Multiple Sleep Latency Tests conducted before and after the first segment of an international trip pattern (24). However, it was correlated with subjective sleepiness as measured by the Stanford Sleepiness Scale. Some studies have shown significant correlations between subjective sleepiness and physiological indicators of sleepiness, including increased alpha and theta activity in the EEG, and slow eye movements (1).

A marked time-of-day variation in subjective fatigue was evident on pretrip days **(Fig. 7)**. Laboratory studies indicate that this type of fatigue measure includes two components: one that parallels the circadian temperature rhythm; and a trend to increasing fatigue with increasing duration of wakefulness (32).

In the daytime short-haul studies, crewmembers were rating their fatigue at the same times in the circadian cycle on pretrip, trip, and posttrip days. It was therefore possible to look for duty-related changes in fatigue. The fixed-wing crews did not report any significant changes (20). The helicopter crews reported feeling greater fatigue by the end of duty days than by the end of pretrip days (15). They also rated their overall fatigue as higher on posttrip days than on pretrip days, which could reflect an accumulation of subjective fatigue across the 4–5 d trips.

In both the overnight cargo and long-haul operations, wakefulness occurred during a different part of the circadian cycle on trip days by comparison with pretrip and posttrip. It was thus not possible to separate the effects of duty-related activities from the effects of sampling a different part of the circadian cycle. Both groups rated their fatigue as higher on trip days than on pretrip days (19,21).

Crewmembers were asked how often they felt that fatigue affected their performance during a typical trip (from 1 = never to 5 = frequently). Responses to this question do not appear to be age-dependent (19), and were not significantly different for the different operations (one-way analysis of variance, $F = 1.32$, $p = 0.27$). The average value of 2.9 indicated that crewmembers considered that fatigue sometimes affected their performance.

Duty-Related Changes in Mood

Each time that they rated their fatigue, crewmembers also rated their mood on 26-adjectives (36,37,40) which were separated into three categories: positive mood, negative mood, and activation (16). Combining pretrip data from 77 crewmembers from all four operations (Fig. 7), ratings on all the mood categories showed significant time-of-day variation (one-way ANOVAs: F (activation) $= 51.83$, $p < 0.001$; F (positive mood)$= 3.90$, $0.01>p > 0.001$; F (negative mood) $= 17.42$, $p < 0.001$). However, looking at each operation separately, i.e., with smaller numbers of crewmembers, positive mood did not vary significantly across pretrip days (17,19–21). Likewise, negative mood did not vary significantly across pretrip days in the data from 12 overnight cargo crewmembers (19). A number of other studies have indicated that circadian variation is not always present in measures of mood states (32), probably because mood can be significantly affected by events occurring at the time that a rating is made.

There were no significant changes in mood ratings associated with the short-haul fixed-wing trips. The short-haul helicopter crews rated their activation as lower by the end of trip days than by the end of pretrip days, and going on duty earlier increased this effect (14). They also rated their negative mood as higher by the end of trip days than by the end of pretrip days, and staying on duty longer increased this effect.

For the overnight cargo and long-haul studies, the confound of duty-related effects and circadian effects on mood ratings could not be disentangled. Overall, overnight cargo crews reported lower activation and more negative mood on trip days than on pretrip days. This is

TABLE IV. DUTY-RELATED CHANGES IN NUTRITIONAL HABITS.

	Mean Short-Haul Fixed-Wing	Mean Short-Haul Helicopter	Mean Overnight Cargo	Mean Long-Haul	F
Appetite on trips	3.01	3.29	2.39	2.72	7.19***
Diet on trips	3.40	2.09	3.13	2.72	18.59***

*** $p < 0.001$.
Note: A value of 3.0 indicates no change on trips by comparison with home.

consistent with findings from other studies that negative changes in mood usually occur when the circadian system is disrupted (32). Long-haul crews reported lower activation, but no change in positive or negative mood, on trip days by comparison with pretrip days.

Overall, overnight cargo crews reported more impact of trips on subjective ratings (poorer sleep quality, less activation, more negative mood) than did long-haul crews who only reported reduced activation. An interesting speculation is that these differences might be linked to the different kinds of circadian disruption associated with the two environments. Overnight cargo crews remained in an environment with 24 h time cues, but were required to be active at an unusual time in it. In contrast, during trips, the long-haul crews had no consistent 24 h time cues from the environment, and their clocks desynchronized from it.

Duty-Related Changes in Dietary Habits

During all operations except overnight cargo, crewmembers increased their daily caffeine consumption on trips by comparison with pretrip (15,19–21). Caffeine is a central nervous system stimulant that can temporarily improve alertness, but can also disrupt sleep, causing longer sleep latencies and lighter, more broken sleep (4). Caffeine is also a diuretic, and may therefore exacerbate problems of dehydration in low humidity cockpits.

Crewmembers were asked (17) to rate how their appetite on trips compared with their appetite at home (from 1 = decreases to 5 = increases), and to rate the quality of their diet on trips compared with home (from 1 = worse to 5 = better). The responses for different operational groups were compared by one-way analysis of variance **(Table IV)**. Post hoc comparisons were made using Tukey tests with Bonferroni correction.

The overnight cargo crews reported significantly poorer appetite on trips than either of the short-haul groups ($p < 0.01$ for both comparisons). The long-haul crews also reported significantly poorer appetite on trips than the helicopter crews ($p < 0.01$). The helicopter crews reported a greater reduction in the quality of their diet on trips than any other group ($p < 0.01$ for all comparisons). The long-haul crews reported signifcantly poorer diet than the short-haul fixed-wing crews ($p < 0.01$).

In summary, the short-haul fixed-wing crews reported that their diet improved somewhat on trips with minimal change in appetite. The helicopter crews reported the greatest increase in appetite on trips and the greatest reduction in the quality of their diet. They were the only group that did not report an increase in snacking on trip days. Food was available in Aberdeen (where each duty day began and ended), and crewmembers could request meals on the rigs, but nothing was available in flight. These findings suggest that attention to the quality and quantity of food available during these operations might be beneficial. The overnight cargo crews reported the greatest reduction in appetite on trips, but with minimal change in the quality of their diet, although they reported eating more snacks. Their reduction in appetite could have been affected by the incomplete adaptation of the circadian clock to night work, since they were on duty at times in the circadian cycle when people would normally be asleep. The long-haul crews reported moderate reductions in appetite and in the quality of diet on trips. They were also the only group that reported eating fewer meals on trip days than on pretrip days. This may reflect problems obtaining suitable meals at unusual local times, as well as the fact that duty sometimes coincided with the part of the circadian cycle where people would normally be asleep.

Duty-Related Changes in Health

Shift workers in other industries generally have higher incidences of health complaints than day workers in comparable jobs, particularly sleep disruption and gastrointestinal problems (1,8,53). **Table V** compares the most common complaints of physical symptoms among crews flying the different operations from a checklist of 20 symptoms. The same four symptoms recurred as the most common in all operations.

In general, reports of symptoms increased on trip days, particularly for back pain and burning eyes (15,19–21). Reports of congested nose were common to all the fixed-wing operations, suggesting a possible effect of altitude and lower cockpit humidity. The helicopter cockpits were often physically stressful with high levels of vibration and thermal loading (14). The higher incidence of back pain among long-haul vs. short-haul fixed-wing crews may be related to the longer flight segments on long-haul (see Table I).

Crewmembers were asked (17) to rate their general health (from 1 = fair to 5 = excellent) and whether they experienced stomach or intestinal problems on trips that they did not experience at home (from 1 = never to 5 = frequently). The responses for different operational groups were compared by one-way analysis of variance **(Table VI)**.

No significant differences were found in either general health, which was rated as excellent, or in the additional incidence of gastrointestinal problems on trips, which was minimal. These findings are likely to have been influenced by the fact that all crewmembers had to undergo regular medical examinations to continue flying.

Crewmembers were also asked to indicate how long

TABLE V. PERCENTAGE OF CREWMEMBERS REPORTING THE MOST COMMON SYMPTOMS.

	Short-Haul Fixed-Wing	Short-Haul Helicopter	Overnight Cargo	Long-Haul
1st Symptom	Headache (27%)	Headache (73%)	Headache (59%)	Headache (56%)
2nd Symptom	Congested nose (20%)	Back pain (32%)	Congested nose (26%)	Congested nose (28%)
3rd Symptom	Back pain (11%)	Burning eyes (18%)	Burning eyes (18%)	Back pain (20%)

it took them to return to what they considered "normal" after a trip. The possible responses were: a) less than a day; b) 1 d; c) 2 d; d) 3 d; e) 4 d or more; f) does not apply. The responses for different operational groups were compared by one-way analysis of variance (Table VI). Post hoc comparisons were made using Tukey tests with Bonferroni correction. The short-haul fixed wing crews reported returning to normal faster than either the overnight cargo or the long-haul crews ($p < 0.0001$ for both comparisons). Long-haul crews took longer to return to normal after a trip than any other group ($p < 0.01$ for all comparisons). This order is consistent with the circadian disruption imposed by the different operations. The short-haul crews remained synchronized to domicile time during trips. The overnight cargo crews only partially adapted to their nocturnal duty times and rapidly reverted to normal on days off. The circadian clocks of the majority of the long-haul crews desynchronized from the environment during trips, and would therefore be expected to take several days to resynchronize to local time after their return home.

DISCUSSION

Comparing the findings from field studies of fatigue in different operations highlights the fact that operational demands vary, as do individual responses to those demands. This precludes a simple universal solution to the problems associated with fatigue in aviation. Each field study identifies specific ways in which fatigue could be reduced. These include possible changes to the Federal Aviation Regulations, alterations in the scheduling practices of individual airlines, and improving the personal coping strategies of individual crewmembers. This implies that responsibility for dealing with issues of fatigue rests with all members of the aviation community.

Countermeasures to reduce the potential impact of fatigue in flight operations can be divided into two categories: preventive strategies which are used prior to duty and during layovers; and operational countermeasures which are used in-flight to help crewmembers maintain their alertness and performance (45). The recommendations that follow are considered in these two categories.

Preventive strategies: Preventive strategies address the major physiological causes of fatigue in flight operations, namely sleep loss and circadian rhythm disruption. Sleep loss, whatever its origins, has detrimental effects on performance. Circadian rhythm disruption is an inevitable consequence of providing round-the-clock services and of transmeridian flight. It can compromise cockpit performance in two ways: through requiring crewmembers to be on duty during the part of the circadian cycle when their performance capacity and alertness are lowest; and through displacement of their sleep to parts of the circadian cycle when sleep quantity and quality, and therefore subsequent waking function, are compromised.

One area in which regulatory action may be warranted is in multi-segment short-haul operations. During the short-haul fixed-wing trips studied, the average daily flight time (4.5 h) was less than half the average daily duty time (10.6 h) and a third of all duty days were longer than 12 h (16,20). The nighttime layovers were the shortest of any of the operations studied (Table I), and the duration of the layover was the single most important scheduling factor contributing to sleep loss. Currently, the FARs define minimum rest requirements based on the number of flight hours. These data suggest that it may be necessary in this environment to regulate duty hours and to relate rest periods to duty hours rather than, or in addition to, flight hours. Since this study was conducted in the mid-1980s, the short-haul operating environment has become considerably more competitive, and the same issues are relevant in the burgeoning regional and commuter airline sectors.

The current Federal Aviation Regulations limit flight hours and determine rest requirements independent of the time-of-day of flying. Based on the data, particularly from the overnight cargo and long-haul operating environments, we would advocate that this position be carefully reconsidered. A number of other countries have already incorporated circadian factors in their flight and duty time regulations (54) and these could be examined as models. It is important to recognize that the FARs serve only as guidelines within which companies decide their scheduling policies through negotiation with their employees. Thus regulatory changes may be necessary, but will certainly be insufficient to deal with all aspects of these problems.

A number of scheduling recommendations arise from

TABLE VI. DUTY-RELATED CHANGES IN HEALTH.

	Mean Short-Haul Fixed-Wing	Mean Short-Haul Helicopter	Mean Overnight Cargo	Mean Long-Haul	F
General health	4.31	4.22	4.40	4.31	0.33
Stomach/intestinal problems	1.78	1.72	1.64	2.13	1.54
Return to normal	1.76	2.22	2.34	3.25	18.49***

*** $p < 0.001$.

the fatigue field studies. One general principle arising from circadian physiology is that the timing of a layover can be as important as its duration in providing adequate time for crewmembers to sleep. As an example, in both the fixed-wing and helicopter short-haul operations, early duty report times were a significant contributor to sleep loss (14–16,20). Crewmembers were unable to fall asleep sufficiently early to compensate, in part because of the evening wake maintenance zone (52). The helicopter crewmembers averaged only 6.4 h of sleep in layovers averaging 16.8 h. In these operations, the time of going on duty the next morning accounted for 41% of the variability in sleep duration, while the layover duration did not have a statistically significant effect (14,15).

In the short-haul fixed-wing schedules there was another common scheduling practice that would be expected to contribute to sleep loss. On average, duty days began progressively earlier across the 3–4 d trips. This effectively restricts the time available for sleep progressively across the trip. In addition to the problem of the evening wake maintenance zone, the biological day programmed by the circadian clock tends to be longer than 24 h, making it easier to adapt to duty days which begin progressively later. Thus, wherever possible, successive duty days should begin at the same time or progressively later, rather than earlier.

During the overnight cargo trips studied, both the timing and duration of layovers had important effects on sleep loss. The earlier a crewmember finished duty in the morning, the longer he was able to sleep before the circadian wakeup signal (around 1400 hours local time). The time of getting off duty accounted for 44% of the variability in the duration of these morning sleep episodes (19), which averaged 2–3 h shorter than pretrip nighttime sleep episodes. The duration of the layover determined whether crewmembers had sufficient time to sleep again before the next night duty. Layovers in which they slept twice averaged 19.3 h, while layovers in which they slept once averaged only 14.8 h.

Scheduling en-route layovers during long-haul operations to ensure that crewmembers obtain adequate sleep is a very complex challenge. Data from the fatigue field study suggest that the factors to be considered include: previous transmeridian flights in the sequence; the direction of the preceding flight; whether it was a daytime or a nighttime flight; the timing of the layover with respect to local night; and the timing of the layover with respect to the circadian cycle of each crewmember. From a physiological point of view, the ideal layover would include a sleep opportunity where the circadian temperature minimum occurred between about 0200 and 0600 hours local time. (The average time of the pretrip temperature minimum in the crewmembers studied was about 0400 hours local time; see Fig. 6). In practice, it is very difficult to predict the time of the temperature minimum through a sequence of non-24 h duty-rest cycles with multiple transmeridian flights. One potential solution would be to make duty-rest schedules multiples of 24 h, in order to keep crews synchronized physiologically to home time. If this approach worked, it would help alleviate the sleep disruption and other problems associated with jet-lag. It would also reduce the range of individual variability in circadian phase, making it easier to design schedules adapted to the needs of a larger proportion of crewmembers, and to predict times of peak sleepiness during duty. The latter would permit more systematic use of operational countermeasures (see below). Although it is theoretically attractive, the feasibility and acceptability of this approach have never been rigorously tested.

Well-designed regulations and scheduling practices are necessary but not sufficient to minimize avoidable fatigue in aviation operations. Individual crewmembers also have a responsibility to try to report for duty well-rested and to make optimal use of their en-route layover time to obtain adequate sleep. In its investigation of a 1993 accident (39) involving the stall, loss of control, forced landing, and overrun of an Embraer EMB-120 RT at Pine Bluff, AR, the National Transportation Safety Board concluded:

> "The crew rest periods scheduled for the trip sequence were within company guidelines and FARs. However, the crew did not take advantage of the rest periods, and the combined effects of cumulatively limited sleep, a demanding day of flying, and a time of day associated with fatigue, were factors in the crew's inadequate judgement and performance".

As a result of its investigation into this accident, and into the 1993 loss of a Douglas DC-8-61 at Guantanamo Bay, Cuba (38), the Board has recommended that education about fatigue and fatigue countermeasures be required for both Part 135 and Part 121 air carriers. Recognizing the importance of education as a key preventive strategy, not only for flight crews but for everyone involved in aviation, the NASA Fatigue Countermeasures Program has developed an education and training module on alertness management in flight operations (17,44).

As mentioned previously, preventive strategies primarily address the two main physiological causes of fatigue, namely sleep loss and circadian disruption. While there is still much to be learned, there is currently a considerable amount of useful information available about practices which promote good sleep, factors which disrupt sleep, sleeping medications, and sleep disorders. By comparison, current understanding about how and when to manipulate the circadian clock is less mature. There is considerable interest in chronobiotics–drugs, hormones (e.g., melatonin), and other treatments (e.g., bright light) that are potentially capable of accelerating the adaptation of the circadian clock to a new duty/rest schedule or time zone. However, there are a number of practical considerations that, for the moment, limit the potential usefulness of chronobiotics for flight crews. The time in the cycle at which a chronobiotic is administered is critical, and opposite effects can be achieved by displacing the dose by several hours. Unfortunately, there is no simple single measurement which can give an indication of exactly where a crewmember is in the circadian cycle at any given time. Chronobiotics used in everyday life must act against a background of all the other environmental time cues to which an individual is exposed. While there are ways of minimizing these extraneous cues (e.g., wearing dark glasses to reduce the effects of sunlight, or minimizing contact with the local social environment), crewmember acceptance of, and compliance with, fatigue countermeasures which require such regimentation of layover activities is a real issue. There are also concerns about the effects of long-term use of potential chronobiotics across the working life of a flight crewmember. More fundamentally, it is not clear that circadian adaptation to local time is necessarily desirable in all situations. Adaptation to a duty/rest schedule then requires readaptation to nighttime sleep and local time on days off. For example, a survey study of 101 Lufthansa flight crews on polar schedules (Frankfurt via Anchorage to Tokyo or Seoul and return) lasting 7–11 d found that the sleep debt accumulated during the trip was less when crewmembers remained longer at the destination layover (49). Presumably sleep improved as the circadian clock adapted to local time. However, readaptation on return to Frankfurt was also slower when crewmembers stayed longer at the destination layover. Finally, none of the chronobiotics currently being considered has been shown to be effective in field tests in any aviation environment.

Operational countermeasures: Operational countermeasures are techniques that crewmembers can use in flight to help maintain their alertness and performance (45). Cockpit napping is currently receiving considerable attention. Observations from the long-haul fatigue field study indicated that about 11% of crewmembers were taking the opportunity to nap when conditions permitted (45). A recent NASA/FAA joint study has demonstrated that providing a preplanned 40-min nap opportunity in flight can improve physiological alertness and performance (on a sustained attention, vigilance-reaction time test) through to descent and landing (46). The limited duration of the nap is important to minimize the possibility of crewmembers entering into deep slow-wave sleep, and thus being prone to sleep inertia should they have to be awakened in an emergency. The FAA currently has a Notice of Proposed Rule Making that would legalize controlled napping in non-augmented three-person long-haul crews. The use of controlled cockpit napping in two-person long-haul crews requires careful consideration.

Except on flights exceeding 12 h, for which additional crewmembers are required, the current FARs (121.543) stipulate that "...each required flight crewmember on flight deck duty must remain at the assigned duty station with seat belt fastened while the aircraft is taking off or landing, and while it is en route." Since physical activity is a good short-term countermeasure for sleepiness, consideration should be given to relaxing this restriction, with appropriate procedural safeguards.

Companies could contribute to operational countermeasures by developing cockpit procedures that pay specific attention to enhancing crew interaction and maximizing the active involvement of crewmembers in the operation. Declines in physiological alertness during long-haul flights have been shown to occur after periods without communication in the cockpit, and to occur simultaneously for the captain and the copilot on many occasions (5). Aircraft manufacturers could assist with this problem through the creative use of automation to enhance cockpit alertness, rather than to diminish it (5,25). Companies also have the opportunity to be proactive in providing education and training for all personnel about alertness management.

The success of any operational fatigue countermeasure ultimately depends on individual flight crewmembers. Appropriate education can provide them with a basis for assessing the feasibility and effectiveness of different countermeasures strategies in relation to their specific operational and personal needs. Admitting to fatigue has often been associated with negative connotations, such as laziness or lack of motivation. Recognizing that it has physiological causes should help to dispel these myths. To be effectively managed, fatigue in the cockpit needs to be dealt with explicitly by the individual and the crew.

ACKNOWLEDGMENTS

The Fatigue Countermeasures Program has benefited from the skills and dedication of many people. The foresight of John Lauber, Charles Billings, Curt Graeber, and Clay Foushee, who established the Program, has given aviation a considerable lead over many other industries in dealing with fatigue issues. Jerry Noga, Don Hudson, and Linda Connell made important contributions. Kevin Gregory, Donna Miller, Roy Smith, Herb Schreiber III, and Bill Carson have provided exceptional support in the area of data management and analysis. Dave Dinges has been an invaluable mentor and colleague. Liz Co has played a key role in the education and training activities of the Program. Long-term funding support from NASA and the FAA have brought this extensive body of work to fruition. The commitment and enthusiasm of the participating airlines and flight crewmembers has continued to be the driving force for the Program. The authors thank Pamela Day and Evynn Blaher for their key contributions to the editing, coordination, and production of this special supplement.

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